An Integrated MEMS Sensor Cluster System for Aerospace Applications

Seun K. Kahng, Michael A. Scott, George B. Beeler, James E. Bartlett, and Richard S. Collins*
NASA, Langley Research Center and *Wyle Laboratories
Hampton, Virginia 23681

Abstract

Efforts to reduce viscous drag on airfoils could results in a considerable saving for the operation of flight vehicles including those of space transportation. This reduction of viscous drag effort requires measurement and active control of boundary layer flow property on an airfoil. Measurement of viscous drag of the boundary layer flow over an airfoil with minimal flow disturbance is achievable with newly developed MEMS sensor clusters. These sensor clusters provide information that can be used to actively control actuators to obtain desired flow properties or design a vehicle to satisfy particular boundary layer flow criteria.

A series of MEMS sensor clusters has been developed with a data acquisition and control module for local measurements of shear stress, pressure, and temperature on an airfoil. The sensor cluster consists of two shear stress sensors, two pressure sensors, and two temperature sensors on a surface area of 1.24 mm x 1.86 mm. Each sensor is 300 microns square and is placed on a flexible polyimide sheet. The shear stress sensor is a polysilicon hot-film resistor, which is insulated by a vacuum cavity of 200 x 200 x 2 microns. The pressure sensors are silicon piezoresistive type, and the temperature sensors are also hot film polysilicon resistors. The total size of the cluster including sensors and electrical leads is 10mm x 10mm x 0.1 mm. A typical sensitivity of shear stress sensor is150 mV/Pascal, the pressure sensors are an absolute type with a measurement range from 9 to 36 psia with 0.8mV/V/psi sensitivity, and the temperature sensors have a measurement resolution of 0.1 degree C.

The sensor clusters are interfaced to a data acquisition and control module that consists of two custom ASICs (Application Specific Integrated Circuits) and a microcontroller. The data acquisition and control module transfers data to a host PC that configures and controls a total of three sensor clusters. Functionality of the entire system has been tested in the laboratory, and preliminary test results are presented.

I. Introduction

Reduction of viscous drag is an important area of study to all flight vehicle operations. It is also important to manage viscous drag on a surface of a flight object by employing a set of actuators, shear stress sensors, and control circuits with a predetermined control algorithm. There are three elements that are required for control of boundary layer flow property on a flight vehicle to attain desired flight efficiency, namely sensors, actuators, and control strategy. This paper addresses the sensor system element.

In wind tunnels and flight vehicles, viscous drag on an airfoil has been determined by means of measuring shear force on a moving platform that is fabricated into an integral part of the vehicle/model, which is a direct measurement scheme. Another method is calculating amount of heat transferred from the surface of the airfoil into the surrounding ambient flow regime, which is an indirect measurement scheme. Direct measurement devices include servomechanism force balance, moving platform MEMS devices, and oil film devices. The indirect measurement devices include heat transfer devices such as hot film/wire gages. Direct measurement devices are preferred, however, they present a gap between the stationary and moving element of the sensor that disturbs boundary layer flow properties. Oil film devices can be considered as a research tool, but it is not a practical measurement tool whose output is used as a feedback signal to control a set of actuators.

Heat transfer devices have the advantage of maintaining the flow property with minimum disturbance, because they do not have gaps or a physical moving component. However, it does not measure the shear stress directly, and a precise relationship between heat transfer and shear stress values are difficult to obtain under practical measurement conditions.

A heat transfer based (thermal type) MEMS shear stress measurement system has been developed for use in wind tunnels and other applications where viscous drag reduction or boundary layer control on an airfoil is desired. The system consists of a sensor cluster which measures shear stress, pressure, and temperature; interfacing electronic circuits for signal processing with a microcontroller; and a host computer (PC) that configures and controls the entire system.

Viscous drag exists in a thin boundary layer adjacent to the airfoil in which tangential flow velocity changes from zero on the airfoil to the free-stream velocity. The change in the velocity across the thin boundary layer is proportional to the shear stress on the airfoil. The viscous drag force, F_d, is a sum of surface shear stress over the airfoil area,

$$F_d = \int \_\, dA \qquad \text{and} \qquad \_ = \_ \{du/dy\}$$

Where τ is shear stress, which is a product of fluid viscosity, _, and gradient of velocity across the boundary layer.

Fluid flow in the boundary layer will alter the convective heat transfer from the sensor, thus changing the temperature of the sensor. The amount of convective heat transfer due to viscous flow can be related to the electrical power transferred into the shear sensor, when the temperature of the shear sensor is maintained at a constant value and the hot film element of the shear sensor is thermally isolated from the airfoil. With the shear stress sensing element kept at a constant temperature, the classical heat transfer model gives a relationship [1] between the power (P) supplied to the sensor element and the shear stress (_) as,

$$P \sim \_^{1/3}$$

This classical macroscale heat transfer model is not always applicable to MEMS sensors with a mircoscale structure. For MEMS devices values of exponent to the shear stress _ ranges considerably higher than 0.33. The values of 0.5 to 1.36 have been observed.

II. Sensor Cluster System

The sensor cluster system has three major building blocks: the sensor cluster, the interfacing electronics, and a host computer as shown in Figure 1. The interfacing electronics receives inputs from the sensors and provide feedback current to maintain a constant temperature to the hot film resistor of the shear stress sensors. It also communicates to host computer through a RS-485 link. The last block of the system is a PC based host processor that configures and controls the entire system.

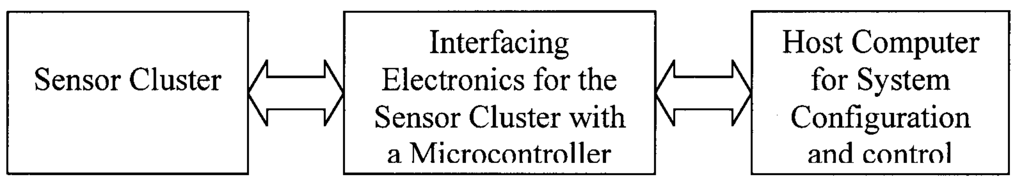

Figure 1. System Block Diagram

II-a. Sensor Cluster

A MEMS sensor cluster has 2 shear stress sensors, 2 pressure sensors, and 2 temperature sensors. These 6 sensors are fabricated on a surface area of 1.24 mm x 1.86 mm.

Figure 2. Sensor Cluster Layout

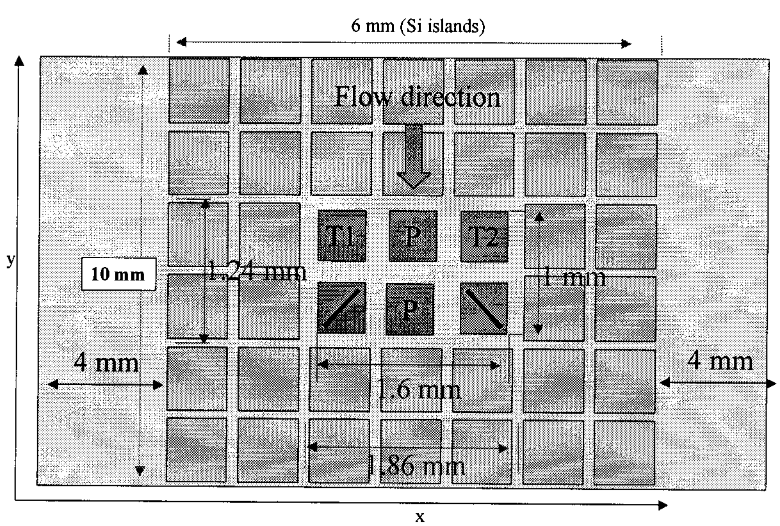

Figure 2 shows a typical layout of the sensor cluster. The 6 sensors are shown in green squares: T1 and T2 are temperature sensors, P's are pressure sensors, and the shear stress sensors are shown with slanted bar in green boxes. Dark yellow square boxes represent silicon islands on a flexible polyimide sheet.

Each sensor is 300 _m square. The shear stress sensors have a 0.25 _m thick 75 _m long polysilicon wire embedded in the 200_m square silicon nitride diaphragm that is isolated by a 2 _m deep vacuum cavity in a silicon substrate [2, 3]. The shear stress sensors are operated in constant temperature mode, and a feedback circuit maintains its temperature at a given point. Both pressure and temperature sensors use a standard interfacing circuit for signal conditioning. The pressure sensors consist of a polysilicon Wheatstone bridge embedded in the diaphragm over a vacuum cavity. One temperature sensor has the same structure as the shear stress sensors, and the other temperature sensor does not have a vacuum cavity. The total thickness of the sensor cluster is 80 _m. Figure 3 shows the sensor cluster on a polyimide sheet with contact pads for electrical connections.

An array of these sensor clusters can be placed on a larger polyimide sheet that covers an area of interests for measurements of shear stress and pressure with temperature. A sensor belt that consists of 3 sensor clusters on a 20" x 6" (50 cm x 15.24 cm) flexible polyimide sheet has been fabricated for wind tunnel studies.

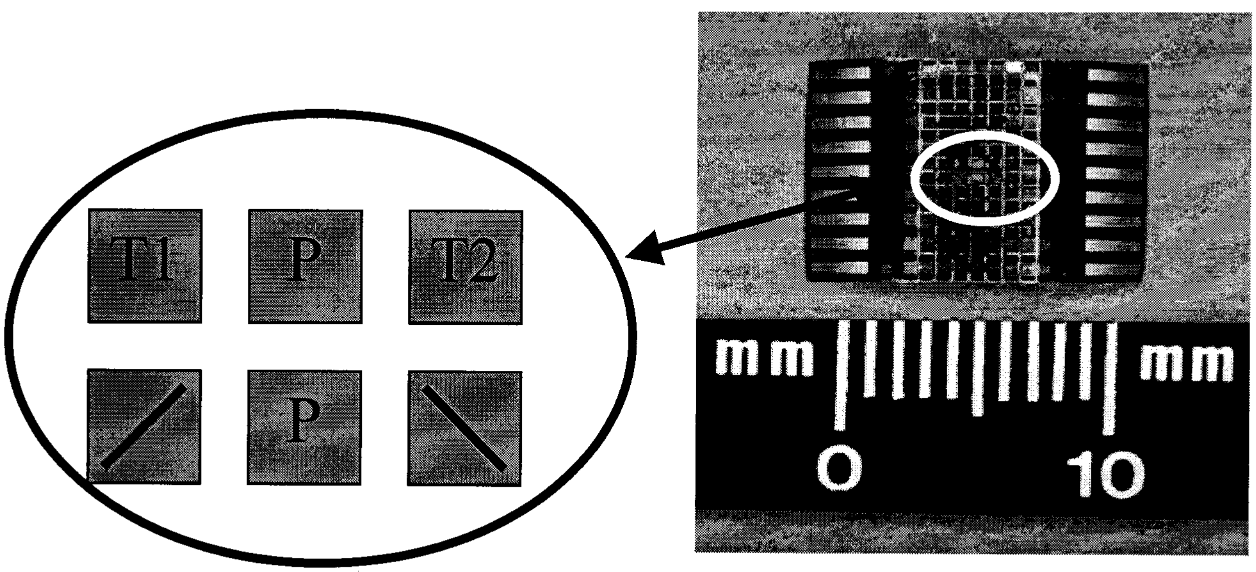

Figure 3. Sensor cluster on a flexible polyimide sheet of 10 mm x 14 mm.

II-b. Data Acquisition and Control Module:

The Data Acquisition and Control Module (DACM) is a multi-channel signal processing and data transfer unit that interfaces to the sensor clusters and communicates with a host computer by a serial RS-485 link. The DACM configuration may be altered by downloads from the host computer and the host can request a data upload from the DACM.

The DACM includes a custom analog front-end integrated circuit, support circuitry, analog-to-digital converter, digital interface circuitry, and microcontroller board. The microcontroller board comprises a microcontroller CPU, memory, and support circuitry. The memory includes RAM, firmware ROM, and a flash memory for nonvolatile storage of default and calibration settings. The user interface is a Windows 95/98 compatible program that provides a means for configuring, testing and operating the system.

III. Experimental Results:

Laboratory evaluation of the sensor clusters exhibited a pressure sensor sensitivity of 0.8mV/V/psi in the pressure range from 9 to 36 psia with a linearity of 0.07% of full-scale output at room temperatures. Response of a typical pressure sensor is shown in Figure 4 [4].

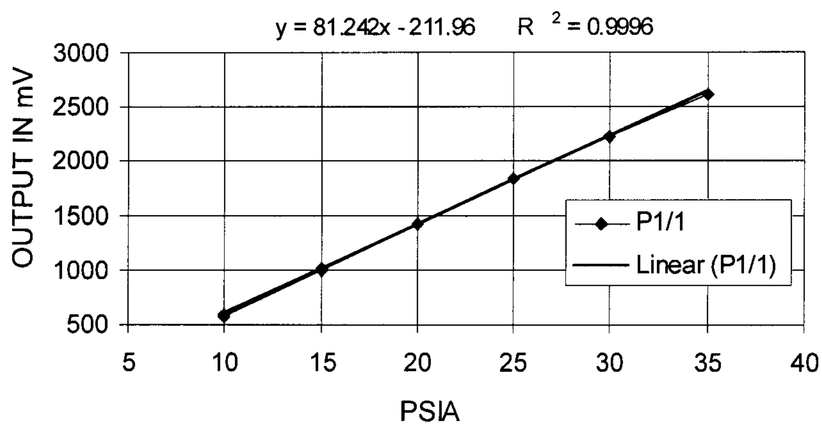

Figure 4. Response of typical pressure sensor

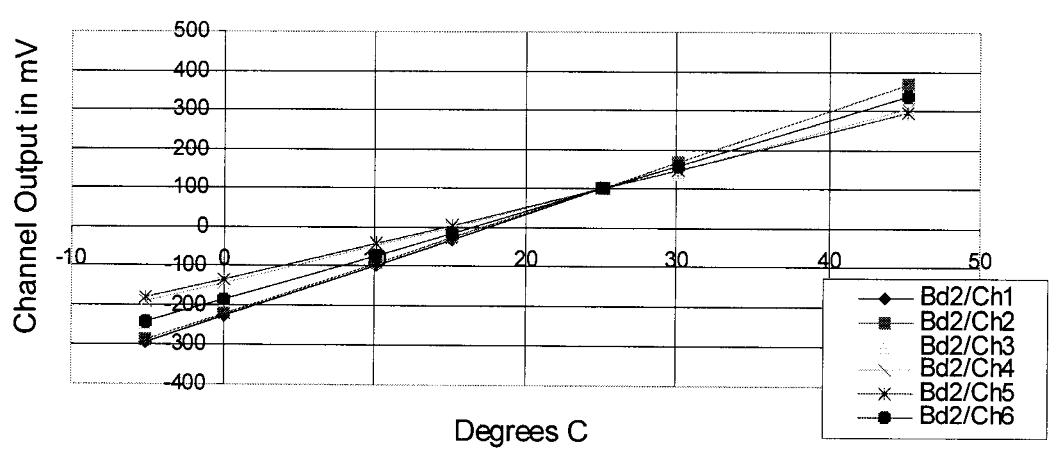

Figure 5. Response of typical temperature sensor

The temperature sensors show a resolution of 0.1 degree C from –5 to +45 degree Celsius. Responses of typical temperature sensors are shown in Figure 5 [4]. The output voltages of the temperature sensors are set at 100 mV at ambient temperature to show coincidence.

The shear stress sensors on a polyimide sheet belt are currently under evaluation and tunnel calibration and repeatability data are not available at this time. Previous shear stress sensors of the same physical configuration have been tested in 20" x 28" LaRC wind tunnel, the calibration and repeatability results are shown in Figure 6.

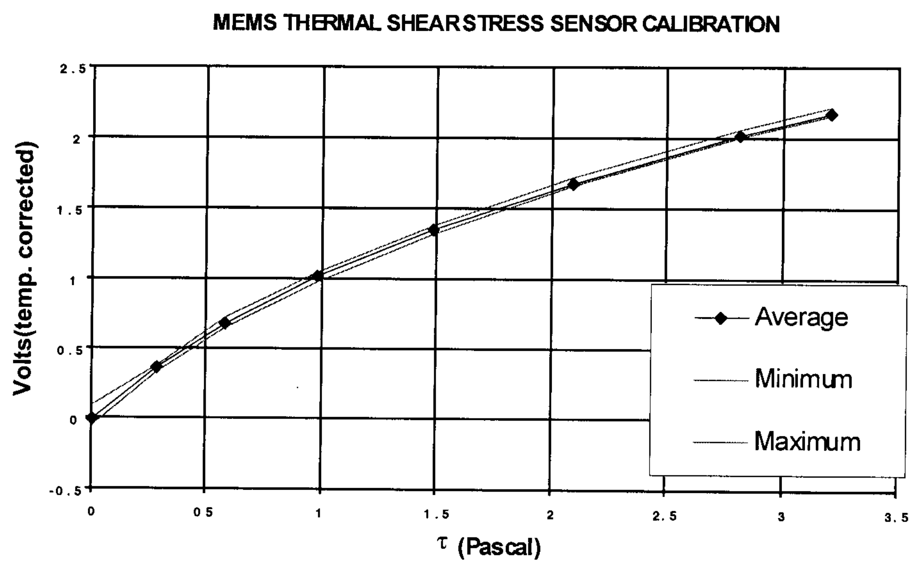

Figure 6. Calibration result of a typical shear stress sensor with respect to a Preston tube.

The shear stress sensors exhibited a typical sensitivity of 150 mV/Pascal. These sensors were mounted on a flat plate that is an integral part of the tunnel test section floor. The outputs from the shear stress sensors were recorded with that of a Preston tube in the tunnel and compared for sensor repeatability and calibrated against the Preston tube results. These wind tunnel tests are conducted in the 20" x 28" Wind Tunnel at Langley Research Center. It is noted that the outputs from the sensors are temperature corrected, and the range of free stream velocity is from 0 to 160 feet per second.

IV. Conclusion and Remarks:

This work has demonstrated an application of MEMS devices to aerodynamic studies on airfoils in wind tunnels. Local measurements of several parameters such as shear stress, pressure, and temperature on the surface of an airfoil using collocated sensors have been made with the MEMS sensors integrated into a flexible insulating sheet.

In wind tunnel applications test articles do not provide a large space for model on-board data modules. A small intelligent and cost effective model embedded data module with wireless data transfer system are desirable for further applications of micro- and nano-sensing devices. In addition applications of Micro/Nano devices for aerospace parameter measurements require a considerable number of interconnects, transfer of large data volume, and packaging of the sensors with test articles. All of these are technical challenges that need to be overcome.

V. References

[1] B.J. Bellhouse et al., "Determination of Mean and Dynamic Skin Friction, Separation and Transition in Low-Speed Flow with a Thin-Film Heated Element", J. Fluid Mechanics, Vol. 24, pp. 379-400, 1966.

[2] F. Jiang et al., "A Michromachined Shear Stress Sensor Array," MEMS '96. pp. 110-115, 1996.

[3] Fukang Jiang, Yu-Chong Tai, Ken Walsh, Tom Tsao, Gwo-Bin Lee, and Chi-Ming Ho, "A Flexible MEMS Technology and its First Application to Shear Stress Sensor Skin," MEMS '97, pp. 465-470, 1997.

[4] Richard S. Collins," Characterization and Test of the UM MEMS Based Instrumentation System," HD6231300-397RO-D8Wyle Laboratories, Hampton, VA. September1999.